<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *2014 International Conference on Probabilistic Methods Applied to Power Systems, PMAAPS 2014, Durham, United Kingdom, 7-10 July 2014*.

Citation for the original published paper:

Westerlund, P., Hilber, P., Lindquist, T. (2014)

A review of methods for condition monitoring, surveys and statistical analyses of disconnectors and circuit breakers.

In: Chris Dent (ed.), *Probabilistic Methods Applied to Power Systems (PMAAPS), 2014 International Conference on* (pp. 1-6). IEEE conference proceedings

<http://dx.doi.org/10.1109/PMAAPS.2014.6960621>

N.B. When citing this work, cite the original published paper.

© 2014 IEEE. Reprinted, with permission, from Westerlund, P., Hilber, P., Lindquist, T. A review of methods for condition monitoring, surveys and statistical analyses of disconnectors and circuit breakers, Proceedings of the International Conference on Probabilistic Methods Applied to Power Systems (PMAAPS), 2014.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-166108>

A review of methods for condition monitoring, surveys and statistical analyses of disconnectors and circuit breakers

Per Westerlund, Patrik Hilber
Department of Electromagnetic Engineering
School of Electrical Engineering
KTH Royal Institute of Technology
Teknikringen 33
SE-100 44 Stockholm
Sweden
email: per.westerlund@ee.kth.se

Tommie Lindquist
Svenska kraftnät
Swedish National Grid
Box 1200
SE-172 24 Sundbyberg
Sweden

Abstract—There is a need for a new survey of condition-monitoring methods for circuit breakers and disconnectors, since during the last two decades less than ten surveys have been carried out. The paper presents several statistical surveys and analyses. The methods of condition monitoring found are reviewed and classified according to the different types of failure identified in the surveys. Some research gaps are identified, such as the prediction of the degradation of the contacts, the signal processing of coil and motor currents and the switching.

I. INTRODUCTION

The unavailability of the Swedish electric distribution networks is in the order of 0.02 %, that is less than 2 hour per year, whereas in the regional networks the average unavailability is around 10 minutes per year [1, p 18, 54]. In order to achieve such a low unavailability, it is needed to plan the maintenance of the electrical equipment thoroughly. The equipment should not fail, nor should the preventive maintenance occur too often, since it requires disconnecting the equipment from the grid. Then good condition monitoring methods are needed to assess the condition of every electrical apparatus.

There are two reviews from Elforsk about condition monitoring in Swedish from the late 90s [2] and [3], which give an overview of different diagnostic methods, with their advantages and disadvantages. They also contain extensive bibliographies, so they should be looked upon even without knowing Swedish. CIGRÉ made a study about condition monitoring in 2000 [4] and another one summarized in [5]. Birlasekaran et al mentioned some condition-monitoring methods for different electrical devices [6]. Kam et al have reviewed methods to prevent reignition in vacuum circuit breakers [7]. They compared the methods and presented seven issues and two approaches for improvement. A CIGRÉ report from 2011 contains about a dozen of references in the area [8]. Reference [9] is a quite superficial review of different condition monitoring techniques. Thus, there are only few reviews from the last 20 years and some of them are quite short and there could be new technologies as some reviews are old.

Condition monitoring is defined in [8, p 20] as the process to get the answers to questions like these:

- Can I postpone maintenance, e.g., on the tap changer?
- Can I make more use of the asset, e.g., operate at higher loading?
- Can I continue to rely on the asset, e.g., continue to operate a suspect unit, but avoid a catastrophic failure?

Hence, the purpose of condition monitoring is to make decisions about preventive maintenance and the possible load that the asset can withstand. Condition monitoring is thus another thing than threshold alarms, whose outcome is to switch off the equipment, since then corrective maintenance must be carried out. Condition monitoring could lead to decision in both directions, to postpone as well as to advance some maintenance actions. Also the decision can sometimes be to reduce the load, sometimes to increase the permitted load. Naturally, the decision can also be to replace the equipment.

In this paper, condition measurement will be used as a general term for all kind of measurements, often or seldom, with installed equipment or with equipment brought to the electric apparatus, that could be used to assess the condition of an electric apparatus with the purpose to plan its maintenance. The measurements could also be done for another purpose, but used also for condition monitoring. Sometimes the term condition measurements is used when the condition monitoring is not continuously done and when it requires the equipment to be disconnected. This term is the opposite of on-line condition monitoring, which is done with permanently installed devices on equipment in use. Here condition measurements are included in the concept of condition monitoring.

In order to choose a failure mode to be monitored, it is important to know how often and which part of a circuit breaker or disconnector fails. Hence, we have looked for statistical surveys and analysis methods of the reliability of circuit breakers and disconnectors. The searches were mainly done in the databases Compendex and Inspec.

II. EQUIPMENT

Within switchgear or switching equipment, this paper covers circuit breakers, which break the current and disconnectors or disconnect switches, which separate parts of the installation when the current has been broken, in order to make maintenance, installation or other work possible. Both the circuit breakers and the disconnector should carry current and be manoeuvrable. So the contacts must be in good condition and the mechanics in order. In addition the circuit breaker should be able to extinguish the arc that appears while opening the circuit. The function of power circuit breakers is described in the book edited by Flurscheim with a chapter about reliability [10]. Bayliss and Hardy deal with different switching phenomena [11]. White covers both the electric path and the operation mechanism with illustrative drawing and photos. It is practically orientated with advice about maintenance [12]. The history of the research on reliability within the electrical field in China is present by Lu, who also mention the relevant Chinese standards and exemplifies one of them [13].

A. Failure statistics about circuit breakers

A vast survey of the failures of circuit breakers was carried out by the Reliability Subcommittee of the IEEE Industry Applications Society [14]. The statistics are grouped by breaker type, voltage, failure mode, failure cause, time since last maintenance and more parameters. CIGRÉ has also produced extensive studies of failures [15], [4], [16], [17], [18], [19], [20], [21], [22] and [23]. The last six ones from 2012 with 281090 circuit breaker years have been summarized in [24], showing a reduction in failure frequency. The Low Voltage Breaker Reliability Working group found that the trip unit and the mechanical parts caused more than two thirds of the failures during maintenance tests [25] or [26].

The population of Norwegian gas-insulated substations (GIS) has been investigated by Istad and Runde [27]. It comprises 618 circuit breakers with about 12000 circuit-breaker years, with 180 failures during the 36 years that GIS have been installed in Norway. It contains the distribution of the failure mode, the cause of failure and the failed component. He has compiled data from Norway and Denmark about circuit breakers [28, pp 35-36].

Another study by Bumblauskas et al comprises 25 models of circuit breakers from a single manufacturer [29]. The population is even further divided according to production year. The total number is about 16000. It introduces some new metrics such as AFTREER (average field two year recorded event rate), which captures the failures during the warranty period. It also deals with FIR (field incident rate) and MTBF (mean time between failures). It gives only some hints on how to analyse failure data. Dementyev et al compiled statistics about planned and unplanned outages affecting circuit breakers of different voltages with 3860 circuit-breaker years [30]. Andrușcă present statistics about different failure types and which parameters should be monitored [31].

The failures of the same type of circuit breaker in a smaller population (1546 breakers with 16384 operating years) has been modelled with a Weibull distribution in [32]. The number of failures is too small for a precise determination of the parameters of the distribution. Tippachon et al studied failures

of protective devices such as circuit breakers, disconnectors and fuses and found that the failures follow a Weibull distribution with a shape parameter between 0.5 and 1 [33]. Choonhapran and Balzer developed a Markov model of circuit breakers with five different failure modes, which follow mainly an exponential distribution [34].

B. Failure statistics about disconnectors

CIGRÉ made a survey of disconnectors and earthing switches with 935204 equipment years [18] and [20]. He has compiled data from Norway and Denmark about disconnectors and switch devices [28, pp 35-36]. Dementyev et al also cover other equipment in the substations as disconnectors [30, table 3].

III. CONDITION MONITORING

The statistics in the preceding section, group the failures in slightly different ways. Here the failures are divided according to the five basic functions of a switching device as in [5]: current carrying, mechanical operation, switching, insulation, and control and auxiliary functions. The last two functions, insulation and control, will not be covered since they are general to most electrical equipment. The first three are covered in the following subsections.

A. Current carrying

In the current path of a circuit breaker or disconnector, there are electric contacts. When the contacts get older, their resistance increases, which leads to a higher temperature. This can cause damage as the material could melt. It is common to measure the resistance, but it could be difficult, since the equipment should in some cases be disconnected. The resistance is low, which demands special instruments. Stanisic has presented a new method to measure the resistance of electric contacts, both in disconnectors and circuit breakers [35]. Runde et al have developed an off-line diagnosis method based on the non-linearity of the resistance of degraded contacts [36]. Vandamme et al have found that the measurement of noise across contacts is an indication of the degradation of the contacts [37].

The temperature is easier to measure, especially by detecting the infrared (IR) radiation. Braunovic et al have shown that the correlation between the temperature rise $\Delta T(t)$ and the resistance $R(t)$ is around 0.9 [38]. Thus it is possible to study any of these parameters for monitoring the condition. The authors also developed an ARIMA (2, 2, 2) model, which was able to predict the temperature within a 0.90-confidence interval. Details about the statistical model are shown by Izmailov et al [39]. A more detailed physical study of life time of closed electrical contacts is [40], which shows that the life time follows the expressions given by the theory, which has been developed by Holm [41].

Muhr et al studied how wind affects the heating of contacts [42]. They found that the temperature rise is not quadratic in the current, but the exponent is somewhere between 1.5 and 1.9. They also provide three heuristic methods to evaluate contacts.

In [43] several statistical methods are tried to predict the contact resistance: moving average, exponential smoothing,

ARIMA and artificial neural networks, which are tested against a simulated time series of the contact resistance. As a separate part of the paper comes a prediction model for the contact resistance, based on the average and the standard error and shown with formulas. The model is tested with the simulated data and with measurements of a relay. Unfortunately, the actual results are not explained referring to the description of the algorithm.

Bagavathiappan et al presented an extensive review of the use of thermography in condition monitoring [44]. It explains also the physics and the different parameters of an infrared camera. Furthermore, it lists relevant standards. There are also examples of applications in different areas and about 30 references to electric and electronic components. Suesut et al have explained the principles of thermography and measured the emissivity of material used in electrical equipment [45]. Jadin and Taib treat the use of thermography for measuring reliability of electrical equipment with 35 references to automatic methods of classification [46].

Lindquist et al have treated the accuracy of thermography and shown that low currents give larger confidence intervals [47]. The temperature rise should be at least 40 degrees centigrade to be detected manually according to Dorovatovski and Liik, who also presented a programme of thermographic inspection [48]. Korendo and Florkowski discuss the problems with thermography and present a toolbox for analysing thermographic images including the possibility to find a trend [49]. Huda and Taib have used both an artificial neural network and traditional multivariate methods to detect defects in the electrical equipment [50]. They have chosen 10 variables from the images, but still the area to be analysed has to be indicated manually, so the method is not fully automatic. It can be calculated how the inspection interval affects the availability [51].

In order to avoid the image processing needed when using thermography, it is possible to place temperature sensors near points, where the temperature can raise. The papers [52] and [53] focus on the measuring sensors put near the contacts and on the wireless transmission of data. The power is supplied to the sensors by induction. They do not explain how the monitored data should be interpreted. Another method is to use a thermopile, which compares the temperature of the object to be monitored with the ambient temperature [54].

The papers in the last paragraph do not cover which decisions can be taken based on the monitoring. However, Chudnovsky presented two case studies with temperature sensors put near the contacts in circuit breakers, where the temperature curves have been studied together with the current [55]. The high temperatures in some phases are explained by a lack of ventilation. Also contact deterioration appears in the figures, in one case due to overload. Furthermore the temperature increase is regressed onto the current. It is shown that the temperature rise can be expressed as a linear function of the current. The higher the slope, the more degraded is the contact and the slope increases abruptly – within a month – with degradation. Livshitz et al explained well the advantages of technology with infrared sensors, how a system is built and what the analysing software should do [56]. They also showed that the time series of the current should be shifted

one hour and smoothed, in order to get a better explanation of the temperature rise.

Korendo and Florkowski present a more complicated algorithm to find contacts that are degrading [49]. They apply it to disconnectors with three contacts for each phase: left head (index 1 refers to it), connector (index 2) and right head (index 3). Then they follow the ratio between the temperature rise of two contacts. Westerlund et al have used IR sensors to follow the condition of disconnector contacts with a model to explain the temperature rise as a function of the current [57].

Temperature sensors and thermography complement each other, since the sensors record the temperature continuously and thus with different loads, while thermography covers more parts of the substation than some specific points [47] and [58].

A simulation based on statistics of failure in the contacts caused by random shocks has been presented in [59], although without a clear conclusion.

B. Mechanical operation

Apart from being able to carry current, the switchgear must be able to switch, which implies a movement of some parts to open or close the electric path. That can occur seldom as with the disconnectors, which are opened few times per decade. In contrast, the circuit breakers connected to reactive elements – shunt capacitors and shunt reactors – are opened several times per day. The failure to open or close on command is observed to be quite frequent for both disconnectors and circuit breakers [18].

The movement can be followed directly by an accelerometer or indirectly as the sound. Then there is a need to compare different opening and closing patterns, which can be done by DTW (dynamic time warping), an algorithm developed for speech recognition [60] and [61]. A different method is used in [62]: short-term spectra and short-term energy distributions. Charbkaew et al used wavelets to compare spectrograms obtained at different conditions and with introduced defects [63]. Meng et al used wavelet packet analysis to detect extended insulation rod in a 35 kV vacuum circuit breaker [64]. Wang used a conventional crosscorrelation [65]. Johal and Mousavi present algorithm for detecting points in coil current waveform, with results from 25 circuit breakers in [66]. In [67] the wavelets were applied only to simulated signals. The image processing tool Mathematical Morphology has been tried to pre-process coil current waveforms [68].

A more direct method is to measure the motor or coil currents during opening and closing. Razi-Kazemi et al take six features (points on the waveform) from the coil current and investigate how different failures affect them [69]. They present several example curves and how a failure detection algorithm can work. Cheng et al have deduced formulas for the mechanics, simulated the trip coil current and tried the formulas in a test set-up [70].

References [71] and [72] provide some figures, analyses and parameter extraction from different waveforms of currents in circuit breakers, that can serve as a basis for further analysis, although no clear explanation is given in the papers. Several signal processing algorithms as change points detection, Fibonacci search algorithm and K-means clustering

algorithm can be used, but they are not explained further [73]. Another method is to study the probability distribution of different parameters and to update the statistics by Bayesian methods [74].

Andrușcă et al follow up their previous paper by experimenting with different operative voltage, solenoid faults and accumulated energy in springs [75]. Two way of calculating the condition of a circuit breaker based of the timing deviations are presented in [76] and [77], but the methods lack examples. A resistance measurement of the electric contacts can be used to determine the position of the contacts during the operation [78]. The combination of a rotational angle sensor and a linear displacement sensor makes it possible to follow the operation directly [54].

C. Switching

For disconnectors, switching refers to completing an open or close operation, since there is no device to extinguish any arcs. Thus we regard switching only as a mechanical operation, which is covered in subsection III-B. For circuit breakers switching means the ability to make and break currents, both the normal load and fault currents. Coventry and Runde explained the failure of the voltage grading capacitors [79]. The voltages are calculated in an electrical model of the circuit breaker and the reactor to which it is connected. The voltages may become some times higher if a reignition or a restrike occurs, which could explain some part of the failure. Kam et al made a survey of methods for preventing reignition in vacuum circuit breakers [7]. It formulates seven questions and explains the answers to them in 38 papers. It goes into detail and compares different papers' statistical models. Rudd et al followed the SF₆ density level in circuit breakers [80]. They also explained how to predict the SF₆ level with a confidence interval.

IV. CONCLUSION

There are several surveys with data about the reliability of circuit breakers and disconnectors. Some surveys model the data statistically with the exponential or the Weibull distribution. Some divide the statistics according to the cause of failure. For the function of carrying current, condition monitoring can be done by thermography or thermal sensors. They complement each other. Still the ability to predict the aging is not yet fully developed. The monitoring of the mechanical operation can be based on the coil and motor currents, or the vibration patterns. In both cases a waveform has to be analysed by conventional or novel signal processing in order to extract relevant features. For the third function to be monitored, which is switching of the current, not so many condition monitoring methods have been found.

ACKNOWLEDGMENT

The research is funded by SweGRIDS. Thanks to the reviewers and to Sajeesh Babu for valuable comments on the text.

REFERENCES

- [1] K. Granath and B. Gustavsson, "Leveranssäkerheten i elnäten 2012. Statistik och analys av elavbrotten i Sverige (Delivery reliability of in the electrical networks 2012. Statistics and analysis of the power outages in Sweden)," Energimarknadsinspektionen (Swedish Energy Markets Inspectorate), Tech. Rep. 4, 2014, in Swedish. [Online]. Available: <http://ei.se/en/Publikationer/Rapporter-och-PM/>
- [2] "Förslag på utvecklingsprojekt. Diagnostiska metoder för tillståndskontroll av transmissions- och distributionsnät. Förstudie (Proposal for development project. Diagnostic methods of condition monitoring av transmission and distribution networks. Preliminary study)," Elforsk, <http://elforsk.se/Rapporter/>, Tech. Rep. 97:16B, September 1997, in Swedish.
- [3] R. Nordin, P. Chasemi, A. Holm, and M. Tapper, "Diagnostiska metoder för kopplande apparater. State-of-the-art (Diagnostic methods for switching apparatus. State-of-the-art)," Elforsk, <http://elforsk.se/Rapporter/>, Tech. Rep. 99:17, September 1999, in Swedish.
- [4] CIGRÉ Working Group 13.08, "Life management of circuit-breakers," Tech. Brochures 165, 2000.
- [5] C. Jones, "CIGRÉ working group 13.09 - monitoring and diagnostic techniques for switching equipment," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, vol. 2, Atlanta, GA, United States, 2001, pp. 1083 – 1087. [Online]. Available: <http://dx.doi.org/10.1109/TDC.2001.971403>
- [6] S. Birlasekaran, S. Choi, and A. Liew, "Overview of diagnostic and condition monitoring techniques for in-service power apparatus," in *Proceedings of EMPD '98. 1998 International Conference on Energy Management and Power Delivery (Cat. No.98EX137)*, vol. vol.2, New York, NY, USA, 1998, pp. 673 – 8. [Online]. Available: <http://dx.doi.org/10.1109/EMPD.1998.702769>
- [7] S. Kam, S. Nielsen, and G. Ledwich, "A systematic review of a statistical vacuum circuit breaker model for condition monitoring," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 2, pp. 620 – 627, 2013. [Online]. Available: <http://dx.doi.org/10.1109/TDEI.2013.6508766>
- [8] CIGRÉ Working Group B3.12, "Obtaining value from on-line substation condition monitoring," Tech. Brochures 462, 2011.
- [9] Q. Zeng, H. Chen, J. L. Bao, Q. Z. Meng, X. J. Lv, and R. J. Zhang, "A survey of condition based maintenance and diagnosis technology in power distribution networks," in *2012 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Piscataway, NJ, USA, 2012, p. 6 pp. [Online]. Available: <http://dx.doi.org/10.1109/ISGT-Asia.2012.6303152>
- [10] C. H. Flurscheim, Ed., *Power circuit breaker theory and design*, ser. Power engineering. Institution of Electrical Engineers, 1982, no. 1.
- [11] C. Bayliss and B. Hardy, "Chapter 13 - switchgear," in *Transmission and Distribution Electrical Engineering*, 4th ed. Oxford: Newnes, 2012, pp. 467 – 541. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/B9780080969121000137>
- [12] J. R. White, "Safety maintenance requirements for power circuit breakers," in *IEEE Conference Record of Annual Pulp and Paper Industry Technical Conference*, Portland, OR, United States, 2012, pp. IEEE Industry Applications Society; Process Industries Department; Pulp Pap. Ind. Comm. Inst. Electr. Electron. Eng. –. [Online]. Available: <http://dx.doi.org/10.1109/PPIC.2012.6293014>
- [13] J. Lu, J. Wang, and Y. Luo, "Survey of the electrical apparatus reliability developments in China," in *IET Conference Publications*, no. 605 CP, Beijing, China, 2012, pp. 91 – 97. [Online]. Available: <http://dx.doi.org/10.1049/cp.2012.0629>
- [14] A. Norris, "Report of circuit breaker reliability survey of industrial and commercial installations," in *IEEE Conference Record of Industrial and Commercial Power Systems Technical Conference*, Chicago, IL, USA, 1989, pp. 1 – 16. [Online]. Available: <http://dx.doi.org/10.1109/ICPS.1989.37228>
- [15] CIGRÉ Working Group 13.06, "Final report of the second international enquiry on high voltage circuit-breaker failures and defects in service," Tech. Brochures 83, 1994.
- [16] CIGRÉ Working Group 23.02, "Report on the second international sur-

- vey on high voltage gas insulated substations (GIS) service experience,” Tech. Brochures 150, 2000.
- [17] CIGRÉ Study Committee A3, “State of the art instrument transformers,” Tech. Brochures 394, 2009.
 - [18] CIGRÉ Working Group A3.06, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, Part 1 – summary and general matters,” Tech. Brochure 509, 2012.
 - [19] —, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, Part 2 – reliability of high voltage SF6 circuit breakers,” Tech. Brochure 510, 2012.
 - [20] —, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, Part 3 – disconnectors and earthing switches,” Tech. Brochure 511, 2012.
 - [21] —, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, Part 4 – instrument transformers,” Tech. Brochure 512, 2012.
 - [22] —, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, part 5 – gas insulated switchgear,” Tech. Brochure 513, 2012.
 - [23] —, “Final report of the 2004–2007 international enquiry on reliability of high voltage equipment, Part 6–GIS practices,” Tech. Brochures 509–514, 2012.
 - [24] M. Runde, “Failure frequencies for high-voltage circuit breakers, disconnectors, earthing switches, instrument transformers, and gas-insulated switchgear,” *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 529 – 530, 2013. [Online]. Available: <http://dx.doi.org/10.1109/TPWRD.2012.2220638>
 - [25] P. O’Donnell, W. Braun, C. Heising, P. Khara, M. Kornblit, and K. McDonald, “Survey results of low voltage circuit breakers as found during maintenance testing,” in *Conference Record of Industrial and Commercial Power Systems Technical Conference*, New Orleans, LA, USA, 1996, pp. 1 – 4.
 - [26] —, “Survey results of low-voltage circuit breakers as found during maintenance testing: Working group report,” *IEEE Transactions on Industry Applications*, vol. 33, no. 5, pp. 1367 – 1369, 1997, discussions on 1370–1372. [Online]. Available: <http://dx.doi.org/10.1109/28.633819>
 - [27] M. Istad and M. Runde, “Thirty-six years of service experience with a national population of gas-insulated substations,” *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2448 – 2454, 2010. [Online]. Available: <http://dx.doi.org/10.1109/TPWRD.2010.2050705>
 - [28] Y. He, “Study and analysis of distribution equipment reliability data. datastudier och analys av tillförlitlighetsdata p komponentnivå fr eldistributionsnät,” Elforsk. Tech. Rep., 2010. [Online]. Available: http://elforsk.se/Rapporter/?rid=10_33_
 - [29] D. Bumblauskas, W. Meeker, and D. Gemmill, “Maintenance and recurrent event analysis of circuit breaker data,” *International Journal of Quality & Reliability Management*, vol. 29, no. 5, pp. 560–575, 2012.
 - [30] Y. Demytyev, M. Misrikhanov, E. Stolyarov, A. Abdurakhmanov, V. Fedorov, and A. Shuntov, “The reliability of the gas-filled 110-750 kv circuit breaker units of substations,” *Power Technology and Engineering*, vol. 45, no. 2, pp. 151 – 154, 2011. [Online]. Available: <http://dx.doi.org/10.1007/s10749-011-0240-6>
 - [31] M. Andrușcă, M. Adam, F. Daniel Irimia, and A. Baraboi, “Aspects about the monitoring and diagnosis of high voltage circuit breakers,” in *EPE 2012 - Proceedings of the 2012 International Conference and Exposition on Electrical and Power Engineering*, Iasi, Romania, 2012, pp. 154 – 158. [Online]. Available: <http://dx.doi.org/10.1109/ICEPE.2012.6463613>
 - [32] T. Lindquist, L. Bertling, and R. Eriksson, “Circuit breaker failure data and reliability modelling,” *IET Generation, Transmission and Distribution*, vol. 2, no. 6, pp. 813–820, 2008.
 - [33] W. Tippachon, R. Boonruang, S. Boonpun, C. Khamtang, N. Klairuang, D. Rerkpreedapong, and J. Hokierti, “Failure analysis of protective devices in power distribution systems for reliability purpose,” in *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, Hong Kong, China, 2007. [Online]. Available: <http://dx.doi.org/10.1109/TENCON.2006.343764>
 - [34] P. Choonhapran and G. Balzer, “Availability of hv circuit-breakers: The application of markov model,” in *2007 IEEE Power Engineering Society General Meeting, PES*, Tampa, FL, United States, 2007. [Online]. Available: <http://dx.doi.org/10.1109/PES.2007.385673>
 - [35] Z. Stanic and R. Neimanis, “A new ultra lightweight method for static and dynamic resistance measurements,” in *Conference Record of IEEE International Symposium on Electrical Insulation*, San Diego, CA, United States, 2010, pp. IEEE Dielectrics and Electrical Insulation Society (DEIS) –. [Online]. Available: <http://dx.doi.org/10.1109/ELINSL.2010.5549820>
 - [36] M. Runde, O. Lillevik, V. Larsen, B. Skyberg, A. Mjelve, and A. Tonstad, “Condition assessment of contacts in gas-insulated substations,” *IEEE Transactions on Power Delivery*, vol. 19, no. 2, pp. 609 – 617, 2004. [Online]. Available: <http://dx.doi.org/10.1109/TPWRD.2003.822942>
 - [37] L. Vandamme, M. G. Perichaud, E. Noguera, Y. Danto, and U. Behner, “1/f noise as a diagnostic tool to investigate the quality of isotropic conductive adhesive bonds,” *IEEE Transactions on Components and Packaging Technologies*, vol. 22, no. 3, pp. 446 – 454, 1999. [Online]. Available: <http://dx.doi.org/10.1109/6144.796549>
 - [38] M. Braunovic, V. Izmailov, A. Naumov, and M. Novoselova, “Estimation of remaining lifetime of power connections using infrared thermography,” in *Proceedings of the 55th IEEE Holm Conference on Electrical Contacts*, 2009, pp. 234 – 239.
 - [39] V. Izmailov, M. Novoselova, and A. Naumov, “Application of statistical methods for forecasting the residual service life of electric connectors,” *Russian Electrical Engineering*, vol. 79, no. 1, pp. 46 – 50, 2008. [Online]. Available: <http://dx.doi.org/10.3103/S1068371208010082>
 - [40] M. Braunovic, V. Izmailov, and M. Novoselova, “A model for life time evaluation of closed electrical contacts,” in *Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts*, Chicago, IL, United States, 2005, pp. 217 – 223. [Online]. Available: <http://dx.doi.org/10.1109/HOLM.2005.1518247>
 - [41] R. Holm, *Electric contacts, theory and applications*, 4th ed. Springer-Verlag, 1967.
 - [42] M. Muhr, S. Pack, S. Jaufer, and H. Lugschitz, “Thermography of aged contacts of high voltage equipment,” *Elektrotechnik und Informationstechnik*, vol. 123, no. 12, pp. 537 – 543, 2006. [Online]. Available: <http://dx.doi.org/10.1007/s00502-006-0393-4>
 - [43] W. Li, K. Li, L. Sun, S. Zhao, and L. Ji, “The test data verifying prediction model of electrical contact,” in *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts*, Seattle, WA, United States, 2004, pp. 429 – 436.
 - [44] S. Bagavathiappan, B. Lahiri, T. Saravanan, J. Philip, and T. Jayakumar, “Infrared thermography for condition monitoring - a review,” *Infrared Phys. Technol. (Netherlands)*, vol. 60, pp. 35 – 55, Sept. 2013, process monitoring;equipment monitoring;machinery monitoring;noninvasive condition monitoring tool;noncontact condition monitoring tool;IRT advances;structural health monitoring;infrared thermography;. [Online]. Available: <http://dx.doi.org/10.1016/j.infrared.2013.03.006>
 - [45] T. Suesut, N. Nunak, T. Nunak, A. Rotruga, and Y. Tuppadung, “Emissivity measurements on material and equipment in electrical distribution system,” in *International Conference on Control, Automation and Systems*, Gyeonggi-do, Korea, Republic of, 2011, pp. 1259 – 1263.
 - [46] M. S. Jadin and S. Taib, “Recent progress in diagnosing the reliability of electrical equipment by using infrared thermography,” *Infrared Physics and Technology*, vol. 55, no. 4, pp. 236 – 245, 2012. [Online]. Available: <http://dx.doi.org/10.1016/j.infrared.2012.03.002>
 - [47] T. Lindquist, L. Bertling, and R. Eriksson, “Estimation of disconnector contact condition for modelling the effect of maintenance and ageing,” in *IEEE Russia Power Tech*, June 2005, pp. 1–7.
 - [48] N. Dorovatovski and O. Liik, “Results of thermographic diagnostics of electric grid contact junctions and generators of oil shale power plants,” *Oil shale*, vol. 22, no. 2, pp. 243–257, 2005.
 - [49] Z. Korendo and M. Florkowski, “Thermography-based diagnostics of power equipment,” *Power Engineering Journal*, vol. 15, no. 1, pp. 33 – 42, 2001.
 - [50] A. N. Huda and S. Taib, “Application of infrared thermography for predictive/preventive maintenance of thermal defect in electrical equipment,” *Applied Thermal Engineering*, vol. 61, no. 2, pp. 220 – 227, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1359431113005322>

- [51] T. Lindquist and L. Bertling, "A method for calculating disconnector contact availability as a function of thermography inspection intervals and load current," in *Cigré Symposium on System Development and Asset Management under Restructuring*, 2007.
- [52] J. Zhang, Y. Gao, and P. Hao, "Research on on-line high-voltage switch contact temperature rise monitoring system based on WSN," in *Advanced Materials Research*, vol. 382, Beijing, China, 2012, pp. 210 – 214. [Online]. Available: <http://dx.doi.org/10.4028/www.scientific.net/AMR.382.210>
- [53] X. Huang, B. Huang, and H. Wang, "Design of compositive on-line monitoring and fault diagnosis system for high-voltage switch cabinet," in *2011 International Conference on Electrical and Control Engineering, ICECE 2011*, Yichang, China, 2011, pp. 156 – 159. [Online]. Available: <http://dx.doi.org/10.1109/ICECENG.2011.6057114>
- [54] Z. Shi, Y. Meng, W. Yang, D. Ding, S. Jia, M. Rong, and Y. Cheng, "On-line condition monitoring system of medium-voltage switchgear," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, vol. 3, no. ASIA PACIFIC, Yokohama, Japan, 2002, pp. 2290 – 2294. [Online]. Available: <http://dx.doi.org/10.1109/TDC.2002.1177821>
- [55] B. H. Chudnovsky, "Electrical contacts condition diagnostics based on wireless temperature monitoring of energized equipment," in *Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts*, Montreal, QC, Canada, 2007, pp. 73 – 80. [Online]. Available: <http://dx.doi.org/10.1109/HOLM.2006.284068>
- [56] A. Livshitz, B. H. Chudnovsky, B. Bukengolts, and B. A. Chudnovsky, "On-line temperature monitoring of power distribution equipment," in *Record of Conference Papers - Annual Petroleum and Chemical Industry Conference*, Denver, CO, United States, 2005, pp. 223 – 231.
- [57] P. Westerlund, P. Hilber, and T. Lindquist, "Condition monitoring of the disconnectors in the electric power transmission grid with temperature sensors," in *MPMM 3rd International Conference on Maintenance Performance Measurement and Management*, 2013.
- [58] T. Lindquist, "Wireless sensors vs thermography — Comparing accuracy and applications," in *SC A3 Colloquium*, no. A3-202 2011. Vienna: CIGRE, 2011.
- [59] R. Medjoudj, D. Aissani, and R. Medjoudj, "Reliability and data analysis of electrical degraded system subject to random shocks," in *ELECO 2011 - 7th International Conference on Electrical and Electronics Engineering*, Bursa, Turkey, 2011, pp. I132 – I136.
- [60] M. Runde, T. Aurud, L. E. Lundgaard, G. E. Ottesen, and K. Faugstad, "Acoustic diagnosis of high voltage circuit-breakers," *IEEE Transactions on Power Delivery*, vol. 7, no. 3, pp. 1306 – 1315, 1992. [Online]. Available: <http://dx.doi.org/10.1109/61.141847>
- [61] H. K. Høidalen and M. Runde, "Continuous monitoring of circuit breakers using vibration analysis," *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2458 – 2465, 2005. [Online]. Available: <http://dx.doi.org/10.1109/TPWRD.2005.855486>
- [62] D. P. Hess, S. Y. Park, M. K. Tangri, S. Vougioukas, A. Soom, V. Demjanenko, R. Acharya, D. Benenson, and S. Wright, "Noninvasive condition assessment and event timing for power circuit breakers," *Power Delivery, IEEE Transactions on*, vol. 7, no. 1, pp. 353–360, 1992.
- [63] N. Charbkaew, T. Suwanasri, T. Bunyagul, and A. Schnettler, "Vibration signal analysis for condition monitoring of puffer-type high-voltage circuit breakers using wavelet transform," *IEEE Transactions on Electrical and Electronic Engineering*, vol. 7, no. 1, pp. 13 – 22, 2012. [Online]. Available: <http://dx.doi.org/10.1002/tee.21690>
- [64] Y. Meng, S. Jia, and M. Rong, "Condition monitoring of vacuum circuit breakers using vibration analysis," in *Proceedings - International Symposium on Discharges and Electrical Insulation in Vacuum, ISDEIV*, vol. 2, Yalta, Ukraine, 2004, pp. 341 – 344. [Online]. Available: <http://dx.doi.org/10.1109/DEIV.2004.1422616>
- [65] Z. Wang, "Use vibration monitoring to identify circuit breakers for condition assessment," in *2009 IEEE/PES Power Systems Conference and Exposition (PSCE 2009)*, Piscataway, NJ, USA, 2009, pp. 1–5. [Online]. Available: <http://dx.doi.org/10.1109/PSCE.2009.4839936>
- [66] H. Johal and M. J. Mousavi, "Coil current analysis method for predictive maintenance of circuit breakers," in *Transmission and Distribution Exposition Conference: 2008 IEEE PES Powering Toward the Future, PIMS 2008*, Chicago, IL, United states, 2008. [Online]. Available: <http://dx.doi.org/10.1109/TDC.2008.4517278>
- [67] X.-g. Hu, Y.-c. Ji, and W.-b. Yu, "The application of wavelet singularity detection in fault diagnosis of high voltage breakers," in *IECON Proceedings (Industrial Electronics Conference)*, vol. 3, Denver, CO, United States, 2001, pp. 490 – 494.
- [68] C. Zhong, R.-g. Yang, and J. Cui, "Mathematical morphology method for pre-processing of coil current waveforms of circuit breakers," in *Proceedings of the 2010 Asia-Pacific Power and Energy Engineering Conference (APPEEC 2010)*, Piscataway, NJ, USA, 2010, pp. 4 pp. –. [Online]. Available: <http://dx.doi.org/10.1109/APPEEC.2010.5448950>
- [69] A. A. Razi-Kazemi, M. Vakilian, K. Niayesh, and M. Lehtonen, "Circuit-breaker automated failure tracking based on coil current signature," *IEEE Transactions on Power Delivery*, vol. 29, no. 1, pp. 283 – 290, 2014. [Online]. Available: <http://dx.doi.org/10.1109/TPWRD.2013.2276630>
- [70] C.-Y. Cheng, L. Chen, and W. Kao, "Diagnosing medium voltage GIS circuit breaker by observing trip coil current with simulation and actual tests," *Electric Power Components and Systems*, vol. 36, no. 2, pp. 181 – 194, 2008. [Online]. Available: <http://dx.doi.org/10.1080/15325000701549285>
- [71] T. Watanabe, T. Sugimoto, H. Imagawa, K. Chan, T. Chew, and S. Qin, "Practical application of diagnostic method of circuit breaker by measuring three current waveforms," in *Proceedings of 2008 International Conference on Condition Monitoring and Diagnosis, CMD 2008*, Beijing, China, 2007, pp. 398 – 401. [Online]. Available: <http://dx.doi.org/10.1109/CMD.2008.4580311>
- [72] M. Kezunovic, C. Nail, Z. Ren, D. Sevcik, J. Lucey, W. Cook, and E. Koch, "Automated circuit breaker monitoring and analysis," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, vol. 1, no. SUMMER, Chicago, IL, United States, 2002, pp. 559 – 564. [Online]. Available: <http://dx.doi.org/10.1109/PSS.2002.1043299>
- [73] Y. Zheng, "Algorithm of change points detection for a trip coil," in *Applied Mechanics and Materials*, vol. 385-386, Tianjin, China, 2013, pp. 597 – 600. [Online]. Available: <http://dx.doi.org/10.4028/www.scientific.net/AMM.385-386.597>
- [74] S. Natti and M. Kezunovic, "Assessing circuit breaker performance using condition-based data and Bayesian approach," *Electric Power Systems Research*, vol. 81, no. 9, pp. 1796 – 1804, 2011. [Online]. Available: <http://dx.doi.org/10.1016/j.epsr.2011.04.010>
- [75] M. Andrușcă, M. Adam, R. Pantelimon, and A. Baraboi, "About diagnosis of circuit breakers," in *2013 - 8th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2013*, Bucharest, Romania, 2013. [Online]. Available: <http://dx.doi.org/10.1109/ATEE.2013.6563368>
- [76] D. Zhang, W. Li, X. Xiong, and R. Liao, "Evaluating condition index and its probability distribution using monitored data of circuit breaker," *Electric Power Components and Systems*, vol. 39, no. 10, pp. 965 – 78, 2011. [Online]. Available: <http://dx.doi.org/10.1080/15325008.2011.552091>
- [77] Y. Guan, M. Kezunovic, P. Dehghanian, and G. Gurralla, "Assessing circuit breaker life cycle using condition-based data," in *IEEE Power and Energy Society General Meeting*, Vancouver, BC, Canada, 2013. [Online]. Available: <http://dx.doi.org/10.1109/PESMG.2013.6673062>
- [78] Z. Stanisic, "Method for static and dynamic resistance measurements of HV circuit breaker," in *IEEE PES Innovative Smart Grid Technologies Conference Europe*, Manchester, United Kingdom, 2011. [Online]. Available: <http://dx.doi.org/10.1109/ISGTEurope.2011.6162618>
- [79] P. Coventry and M. Runde, "Electrical stresses on circuit-breaker voltage grading capacitors caused by unequal voltage sharing during switching operations," *European Transactions on Electrical Power*, vol. 21, no. 1, pp. 174 – 179, 2011. [Online]. Available: <http://dx.doi.org/10.1002/etep.426>
- [80] S. Rudd, V. Catterson, S. McArthur, and C. Johnstone, "Circuit breaker prognostics using sf6 data," in *IEEE Power and Energy Society General Meeting*, Detroit, MI, United States, 2011. [Online]. Available: <http://dx.doi.org/10.1109/PES.2011.6039599>